CONFIDENTIAL

Copy 6
RM E55K23
c2

NACA RM E55K23

UNCLASSIFIED

NACA

RESEARCH MEMORANDUM

EFFECT OF INLET-GUIDE-VANE ANGLE ON PERFORMANCE CHARACTERISTICS OF A 13-STAGE AXIAL-FLOW COMPRESSOR IN A TURBOJET ENGINE

By Arthur A. Medeiros and Howard F. Calvert

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFICATION CHANGED

To UNCLASSIFIED

By authority of TPA #45 Date Apr. 12, 1961

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

May 22, 1956

CONFIDENTIAL

NASA Technical Library
3 1176 01435 4493

3901

CV-1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF INLET-GUIDE-VANE ANGLE ON PERFORMANCE CHARACTERISTICS OF A 13-STAGE AXIAL-FLOW COMPRESSOR IN A TURBOJET ENGINE

By Arthur A. Medeiros and Howard F. Calvert

SUMMARY

The effect of adjusting compressor inlet-guide-vane angle on over-all compressor performance, stage performance, engine thrust, and specific fuel consumption was investigated in a 7000-pound-thrust turbojet engine. Data were obtained at design guide-vane angle, 7° below design and 14° and 29° above design. Increasing the guide-vane angle decreased the weight flow at the higher compressor speeds. The maximum design-speed efficiency was obtained with the standard guide-vane angle. The pressure ratio for a given nozzle area was decreased at all speeds by increasing the guide-vane angle. The maximum speed at which rotating stall was encountered decreased with increasing guide-vane turning, except for the 29°-angle position. In addition, the 29° guide-vane angle produced hub stall, whereas the other guide-vane settings produced tip stall.

Changing the guide-vane angle had no effect on stage performance characteristics, other than the first stage. Increasing guide-vane turning decreased the maximum flow, pressure, and temperature coefficients for the first stage.

Maximum thrust at design speed was obtained with the -7° guide-vane angle, and minimum design-speed fuel consumption was obtained with the standard guide-vane setting.

INTRODUCTION

The use of variable-geometry features has become common practice in modern turbojet engines. The primary reason for using variable geometry has been to improve the accelerating characteristics of the engine. Even in engines with good acceleration characteristics, variable engine geometry may be desirable to delay the occurrence of rotating stall and relieve the attendant blade-vibration problems (ref. 1). Some of the devices that have been used or considered are (1) retractable

[redacted]

inlet-air baffles, (2) adjustable compressor-inlet guide vanes, (3) adjustable compressor stator blades, (4) compressor interstage air bleed, (5) compressor discharge air bleed, (6) adjustable turbine stators, and (7) adjustable exhaust-nozzle areas.

The retractable inlet-air baffle is used primarily for the purpose of disrupting the periodicity of rotating stall that may result in resonant blade vibrations. Reference 2 presents some experimental evidence of the effectiveness of the baffle in decreasing rotor blade-vibration stresses due to rotating stall. Reference 3 indicates that the inlet-air baffle can also, in some cases, improve engine acceleration in the critical intermediate-speed range. 3901

Adjustable inlet guide vanes, adjustable compressor stator blades, and interstage air bleed are all effective in improving engine acceleration and delaying rotating stall, by improving the matching of compressor stages at flow conditions other than design. The effects of resetting guide vanes and stator blades on compressor performance are given in references 4 to 6. The effects of interstage air bleed on engine acceleration are evaluated analytically in reference 7.

The last three methods, compressor discharge air bleed, adjustable turbine stators, and adjustable exhaust-nozzle area, allow the equilibrium operating point of a given speed to be at a lower compressor pressure ratio, thereby increasing the margin between equilibrium operation and the stall-limit line of the compressor and permitting more rapid engine accelerations. Because these methods have no effect on the compressor performance, they are not very effective in controlling severe blade vibrations due to rotating stall. References 8, 9, and 10 present analytical evaluations of compressor discharge bleed, turbine stator adjustment, and exhaust-nozzle-area adjustment, respectively.

This report presents the effect of inlet-guide-vane-angle adjustment on the over-all compressor performance, compressor stage performance, engine thrust, and specific fuel consumption, and reference 11 presents the rotating-stall and blade-vibration characteristics for a 7000-pound-thrust turbojet engine with a 13-stage compressor producing a design pressure ratio of approximately 7. The guide-vane angle was varied from 7° below to 29° above the design setting. Data were obtained at speeds from 55 to 100 percent of rated equivalent speed. At each speed and guide-vane angle, data were obtained over the permissible range of exhaust-nozzle areas.

APPARATUS AND INSTRUMENTATION

Engine

The turbojet engine used in this investigation had a sea-level static thrust of about 7000 pounds. The 13-stage axial-flow compressor

CV-1 back 3901

handled approximately 120 pounds of air per second and produced a pressure ratio of about 7. The standard production compressor for this engine was fitted with fixed-position inlet guide vanes. For this investigation they were replaced by a vane assembly in which the guide-vane angle could be varied 36°. The geometry of the two vane assemblies was similar, except that the available variable-angle assembly consisted of 72 instead of 48 vanes as in the standard fixed-angle assembly. The zero position of the variable-vane assembly was set so the flow conditions through the engine were as close to standard engine conditions as possible. The guide-vane actuating mechanism was positioned so the guide vanes could be moved from 7° below to 29° above the zero guide-vane setting. The angle was measured with respect to the axis of the engine, so that the higher angle indicates more turning of the air through the guide vane. Four guide-vane positions were investigated, -7°, 0°, 14°, and 29°.

Installation

The engine was installed in a sea-level test stand; therefore, the inlet conditions were those of the ambient atmosphere. A variable-area exhaust nozzle was used so that a range of compressor operation could be obtained. The nozzle was sized so that with maximum area the engine operated at design temperature ratio at equivalent design speed and zero guide-vane angle.

Instrumentation

The locations of the pressure and temperature instrumentation used in this investigation are shown in figure 1. Total pressure and temperature were measured at the inlet and discharge of the compressor and in the tail pipe. Measurements were also made at the discharge of the first, second, fourth, and ninth stages. The compressor weight flow was computed from the data at station 1. Rotating stall was detected by use of the constant-current hot-wire-anemometer system described in reference 12. Anemometer probes were located in the stator passages of the first through sixth stages.

PROCEDURE

At each guide-vane angle (-7°, 0°, 14°, and 29°), equivalent engine speeds from 55 to 100 percent of design were run in increments of 5 percent. At each of these speeds, data were obtained with the nozzle at the maximum-area position. This was the area required for rated-temperature operation at rated speed with the zero guide-vane angle and standard sea-level inlet conditions. In order to obtain interstage data

over a range of compressor operation, the nozzle area was decreased until either limiting tail-pipe temperature or the limit of the exhaust-nozzle linkage was encountered.

RESULTS AND DISCUSSION

Over-All Compressor Performance

The over-all performance of the compressor in terms of equivalent weight flow, total-pressure ratio, and adiabatic temperature-rise efficiency is shown in figure 2 as a function of percentage of rated equivalent speed for the rated nozzle area as determined for the zero guide-vane setting. At design speed a 29°-increase in guide-vane angle produces a 27.5-percent decrease in weight flow, whereas a 7°-decrease in guide-vane angle produces a 3.2-percent increase in flow (fig. 2(a)). At all speeds above 85 percent of design, increasing the guide-vane turning decreases the weight flow. At speeds below about 70 percent of design, the highest flow is obtained with the 14° guide-vane angle. 3901

The total-pressure ratio and compressor efficiency are shown in figure 2(b). As the guide-vane angle is increased, the total-pressure ratio decreases. This is true over the entire speed range, although the effect is more pronounced at the higher speeds. For the guide-vane angles investigated, the highest compressor efficiency at design speed, 82.2 percent, is obtained with the standard guide-vane setting. At the lower speeds (below 80 percent of design) the 14° guide-vane angle produces the highest efficiency.

Also shown in figure 2 are the maximum speeds at which rotating stall was encountered along the rated-nozzle-area operating lines for the various guide-vane angles. With the standard guide-vane setting, stall was detected at speeds up to 70 percent of rated. Decreasing the guide-vane angle 7° increased the maximum speed at which stall was encountered to 75 percent of design. Increasing the guide-vane angle to 14° reduced the maximum stall speed to 67.5 percent; however, a further increase in guide-vane angle to 29° resulted in a maximum-stall-speed increase to 72 percent of rated. In addition, the 29° guide-vane angle produced a hub stall (stall-region flow deficiency highest at the hub of the compressor), whereas a tip stall was measured with the other three guide-vane angles. This suggests that increasing guide-vane turning decreases the blade loading at the tip of the inlet stages, and that with sufficient increase in guide-vane turning the hub loading of either the first or some succeeding stage can be made critical. The changes in the rotating-stall characteristics of this compressor, particularly with regard to rotor blade vibration, are discussed further in reference 11.

The data of figure 2 indicate that, with the exhaust-nozzle area used herein, design-speed weight flow of this compressor can be increased

3901

slightly, with some decrease in design-point compressor efficiency, by decreasing the guide-vane angle 7° from the standard setting. Low-speed compressor performance and probably engine acceleration would be adversely affected by such a decrease in guide-vane turning. In addition, rotating stall would persist to higher speeds with the lower guide-vane angle. Part-speed performance can be improved and stall restricted to a slightly lower speed by increasing the guide-vane turning. However, these data indicate that for this compressor there is an optimum, so that excessive guide-vane resetting can result in an increase in the maximum speed at which stall is encountered. Increased guide-vane turning decreases the weight flow and compressor efficiency at design speed.

Stage Characteristics

Stage performance characteristics were measured with each of the four guide-vane angles for the first stage, the second stage, stages 3 and 4, stages 5 to 9, and stages 10 to 13. The performance is shown in figures 3 to 7 with temperature and pressure coefficients as functions of flow coefficient. These performance parameters are defined in reference 1.

The pertinent performance data which indicate the stage characteristics for each of the groups with the four guide-vane angles are listed in the following table. These include the maximum flow coefficient, the maximum pressure coefficient, and the flow and temperature coefficients at maximum pressure coefficient.

SUMMARY OF PERTINENT STAGE-PERFORMANCE DATA WITH VARIOUS GUIDE-VANE ANGLES

Stages	Maximum flow coefficient				Maximum pressure coefficient				Flow coefficient at maximum pressure coefficient[a]				Temperature coefficient at maximum pressure coefficient[a]			
	Guide-vane angle, deg															
	-7	0	14	29	-7	0	14	29	-7	0	14	29	-7	0	14	29
1	0.52	0.50	0.46	0.39	0.44	0.42	0.34	0.24	0.45	0.44	0.37	0.26	0.45	0.43	0.35	0.27
2	.50	.50	.50	.50	.28	.29	.31	.30	.44	.42	.42	.42	.37	.39	.39	.37
3 to 4	.49	.49	.49	.48	.34	.34	.33	.33	.41	.40	.40	.43	.37	.38	.38	.37
5 to 9	.46	.46	.46	.46	.29	.29	.30	.29	.41	.39	.39	.40	.34	.34	.34	.34
10 to 13	.40	.40	.40	.39	.12	.13	.14	.14	.37	.37	.36	.36	.15	.15	.16	.18

[a]Where maximum-pressure coefficient is obtained over range of flow coefficient, average flow coefficient for maximum pressure coefficient is listed.

In the first stage, the maximum flow and pressure coefficients both decrease with increased guide-vane turning. The flow and temperature-rise coefficients at maximum pressure coefficient for the first stage also decrease with increased guide-vane turning. The performance characteristics of all other stages in the compressor are essentially unaffected by guide-vane turning. These results are consistent with those of references 4 to 6.

The design vector diagrams and blading details were not available for this compressor, so that an analysis of the effect of guide-vane turning on compressor characteristics could not be made; however, some of the results obtained can be explained on the basis of analyses made on other axial-flow compressors (refs. 4 to 6). These analyses were based on satisfying the simple-radial-equilibrium condition between each blade row. As guide-vane turning is increased, the radial-equilibrium condition requires that the axial velocity at the tip decrease relative to that at the hub. The decrease in axial velocity at the tip tends to compensate for the increased guide-vane turning, so that little change 3901
in angle of attack occurs at the tip of the first rotor. At the hub sections the axial velocity increases with increased guide-vane turning, thereby producing a large angle-of-attack decrease. Because of the large decrease in angle of attack at the hub, the first-stage rotor cannot pass the design weight flow at design speed; therefore, the maximum flow coefficient for the stage decreases with increasing guide-vane turning.

Since a decreased tip axial velocity is required to satisfy the radial-equilibrium condition with increased guide-vane turning, and because the higher-guide-vane-turning configuration operates at a lower design-speed weight flow (or inlet axial-velocity level), the tip angle of attack on the first rotor row is usually higher with the higher guide-vane turning. Inasmuch as the first-rotor tip sections are usually most critical with respect to stall, it appears that the increased tip angle of attack with increased guide-vane turning makes the tip sections even more critical, so that no improvement in stall-free speed range results. Angle of attack, however, is not a sufficient criterion for blade-row stall; blade-element loading must also be considered. A velocity-diagram parameter for blade loading developed in reference 13 has been labeled diffusion or D factor. An analysis of the flow across a first-rotor blade row with various guide-vane angles (ref. 6) shows that increased guide-vane turning decreases the loading or D factor along the whole blade span. Because of this decreased blade loading, increased guide-vane turning increases the stall-free speed range and improves low-speed performance. The lack of vector diagrams and blading details for the compressor used herein precludes the possibility of determining the reason for the hub stall encountered with the 29° guide-vane angle.

Guide-vane turning has little effect on the axial-velocity distribution after the first rotor (ref. 6). This, plus the fact that the angle distribution after the first stator is unaffected by guide-vane turning, means that the performance of all stages after the first stage will have essentially the same performance at a given flow coefficient regardless of the guide-vane angle.

3901

Over-All Engine Performance

The equivalent thrust and specific fuel consumption obtained with the various guide-vane angles and the rated nozzle area are shown in figure 8 as functions of percentage of equivalent design speed. The thrust and specific fuel consumption have been divided by the respective values obtained at rated speed with the standard guide-vane angle. At design speed the thrust can be increased about 8 percent by decreasing the guide-vane angle from 0° to -7°. The increase in thrust is accompanied by a 2-percent increase in fuel consumption. Large decreases in design-speed thrust (up to 50 percent with the 29° guide-vane angle) can be obtained by increasing the guide-vane turning. Although this method of thrust control cannot be considered for cruise because of the large increases in specific fuel consumption that are incurred, it would be possible to use the adjustable guide vane to reduce landing thrust. This method would have an advantage over obtaining decreased thrust by engine speed decreases, because the thrust would be rapidly recoverable in the event of any type of wave-off.

SUMMARY OF RESULTS

An investigation of the effects of adjusting inlet-guide-vane angle on over-all compressor, stage, and over-all engine performances gave the following results:

1. At high compressor speeds (above 85 percent of design) increasing the guide-vane turning decreased the weight flow. The weight flow at design speed was decreased 27.5 percent by increasing the guide-vane angle from 0° to 29°. A guide-vane-angle decrease of 7° from standard produced a 3.2-percent increase in weight flow.

2. The total-pressure ratio was decreased at all speeds with increased guide-vane turning. The highest compressor efficiency at high speeds was obtained with the standard guide-vane angle; at low speeds the 14° guide-vane angle produced the highest compressor efficiencies.

3. Increasing the guide-vane angle from -7° to 14° decreased the maximum speed at which rotating stall was encountered along the rated-nozzle-area operating line from 75 to 67.5 percent of rated equivalent speed. A further increase in guide-vane setting to 29° increased the maximum stall speed to 72 percent of rated and changed the stall configuration from a tip to a hub stall.

4. Increased guide-vane turning reduced the maximum flow coefficient, pressure coefficient, and temperature coefficient for the first stage. The performance of all other stages was essentially unaffected by guide-vane turning.

5. Design-speed thrust was increased 8 percent and specific fuel consumption increased 2 percent by decreasing the guide-vane angle 7° from standard. A 50-percent decrease in design-speed thrust was obtained by increasing the guide-vane angle 29° from standard.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 23, 1955

3901

REFERENCES

1. Calvert, Howard F., Braithwaite, Willis M., and Medeiros, Arthur A.: Rotating-Stall and Rotor-Blade-Vibration Survey of a 13-Stage Axial-Flow Compressor in a Turbojet Engine. NACA RM E54J18, 1955.

2. Huntley, S. C., Huppert, Merle C., and Calvert, Howard F.: Effect of Inlet-Air Baffles on Rotating-Stall and Stress Characteristics of an Axial-Flow Compressor in a Turbojet Engine. NACA RM E54G09, 1955.

3. Filippi, Richard E., and Lucas, James G.: Effect of Compressor-Inlet Area Blockage on Performance of an Experimental Compressor and a Hypothetical Engine. NACA RM E54L01, 1955.

4. Medeiros, Arthur A., Benser, William A., and Hatch, James E.: Analysis of Off-Design Performance of a 16-Stage Axial-Flow Compressor with Various Blade Modifications. NACA RM E52L03, 1953.

5. Budinger, Ray E., and Serovy, George K.: Investigation of a 10-Stage Subsonic Axial-Flow Research Compressor. V - Effect of Reducing Inlet-Guide-Vane Turning on Over-All and Inlet-Stage Performance. NACA RM E53H10, 1954.

6. Budinger, Ray E., and Kaufman, Harold R.: Investigation of the Performance of a Turbojet Engine with Variable-Position Inlet Guide Vanes. NACA RM E54L23a, 1955.

7. Rebeske, John J., Jr., and Dugan, James F., Jr.: Acceleration of High-Pressure-Ratio Single-Spool Turbojet Engine as Determined from Component Performance Characteristics. II - Effect of Compressor Interstage Air Bleed. NACA RM E53E06, 1953.

8. Rebeske, John J., Jr., and Rohlik, Harold E.: Acceleration of High-Pressure-Ratio Single-Spool Turbojet Engine as Determined from Component Performance Characteristics. I - Effect of Air Bleed at Compressor Outlet. NACA RM E53A09, 1953.

9. Rohlik, Harold E., and Rebeske, John J.: Acceleration of High-Pressure-Ratio Single-Spool Turbojet Engine as Determined from Component Performance Characteristics. III - Effect of Turbine Stator Adjustment. NACA RM E54F04, 1954.

10. Rebeske, John J., Jr., and Dugan, James F., Jr.: Matched Performance Characteristics of a 16-Stage Axial-Flow Compressor and a 3-Stage Turbine. NACA RM E52H18, 1953.

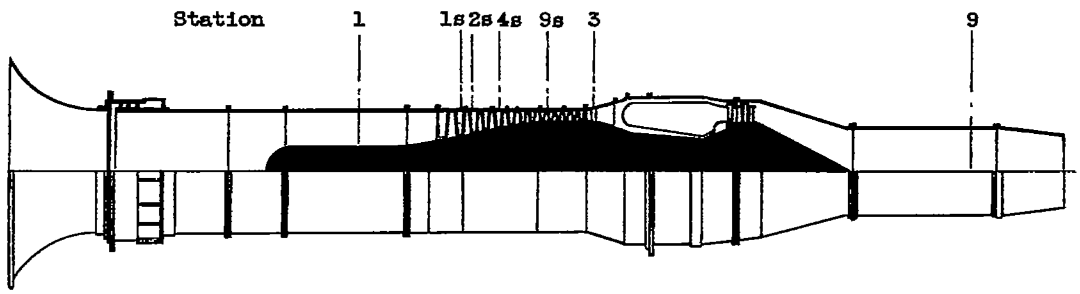
11. Calvert, Howard F., Medeiros, Arthur A., and Johnson, Donald: Effect of Inlet-Guide-Vane Angle on Blade Vibration and Rotating Stall of 13-Stage Axial-Flow Compressor in Turbojet Engine. NACA RM E55K03, 1956.

12. Shepard, Charles E.: A Self-Excited, Alternating-Current, Constant-Temperature Hot-Wire Anemometer. NACA TN 3406, 1955.

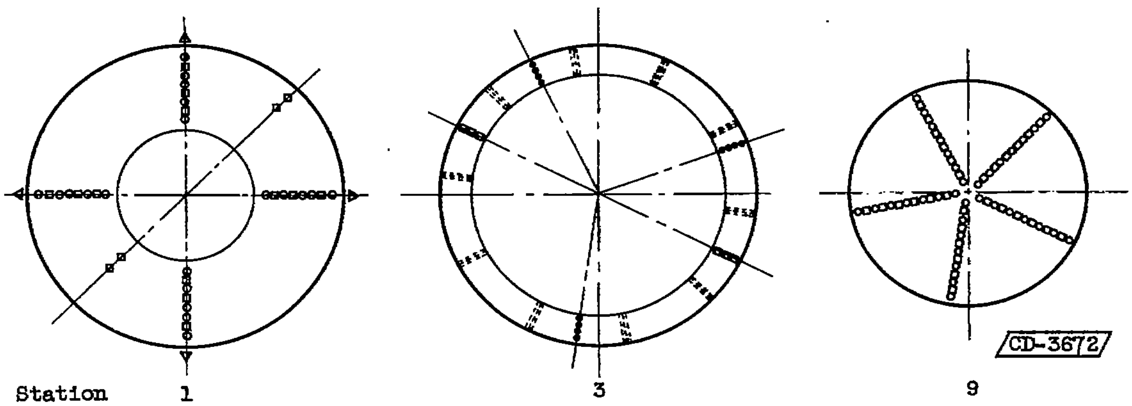
13. Lieblein, Seymour, Schwenk, Francis C., and Broderick, Robert L.: Diffusion Factor for Estimating Losses and Limiting Blade Loadings in Axial-Flow-Compressor Blade Elements. NACA RM E53D01, 1953.

3901
CV-2

3901



(a) Cross section of engine.



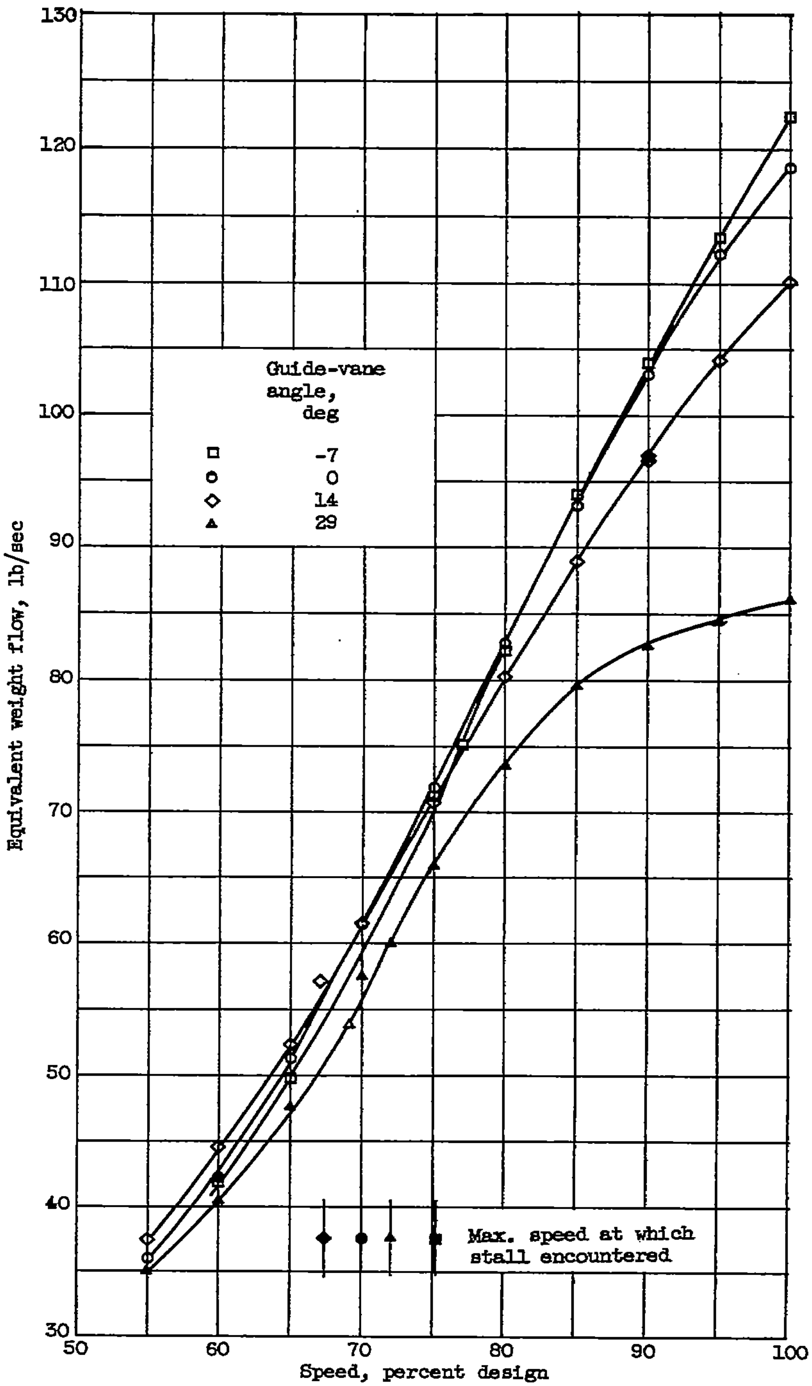
(b) Views of several stations (looking downstream).

	Type of probe	Station						
		1	1s	2s	4s	9s	3	9
○	Total pressure	20	5	5	5	3	12	35
□	Total temperature	12	5	5	5	3	6	30
◇	Stream static	4	-	-	-	-	-	-
△	Wall static tap	4	-	-	-	-	-	-

Figure 1. - Cross section of engine showing stations at which instrumentation was installed.

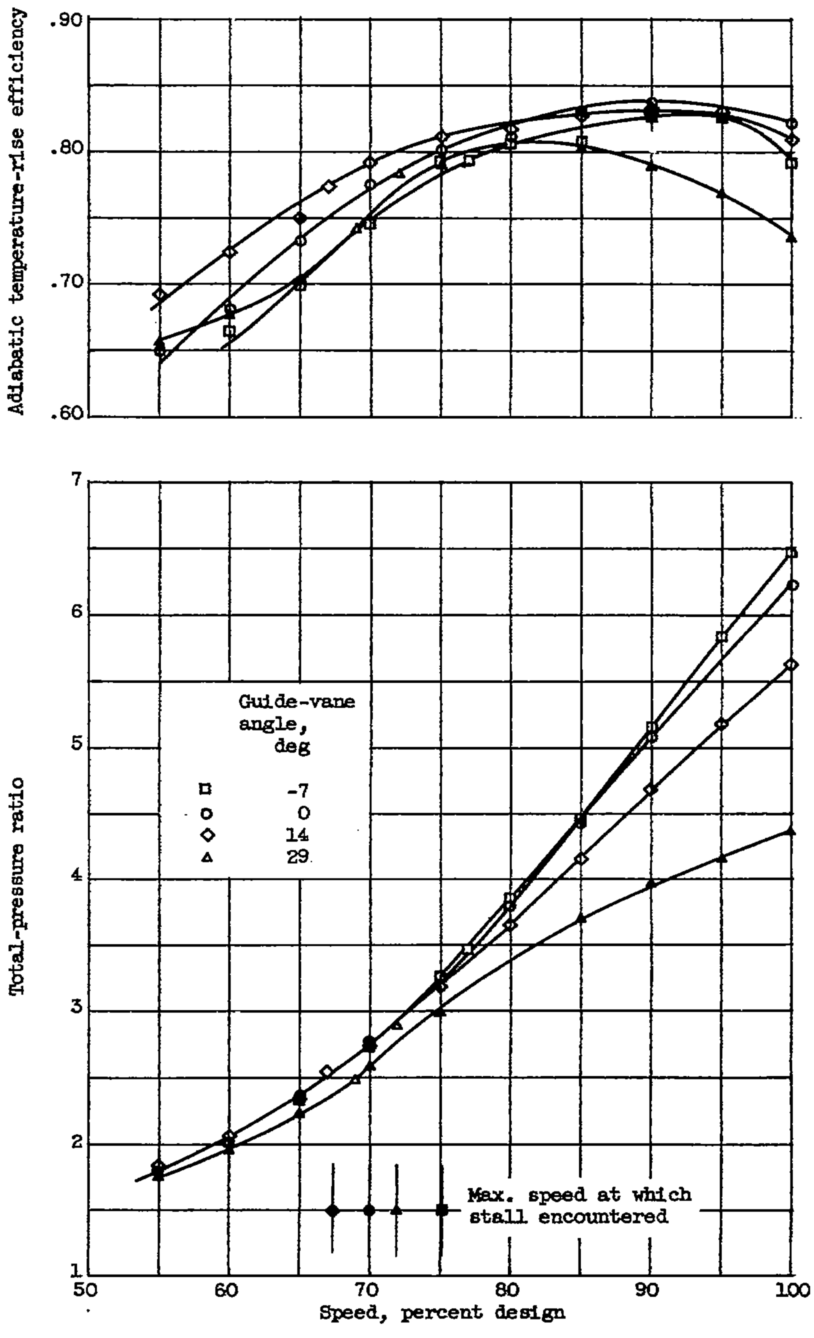
3901

CV-2 back



(a) Equivalent weight flow.

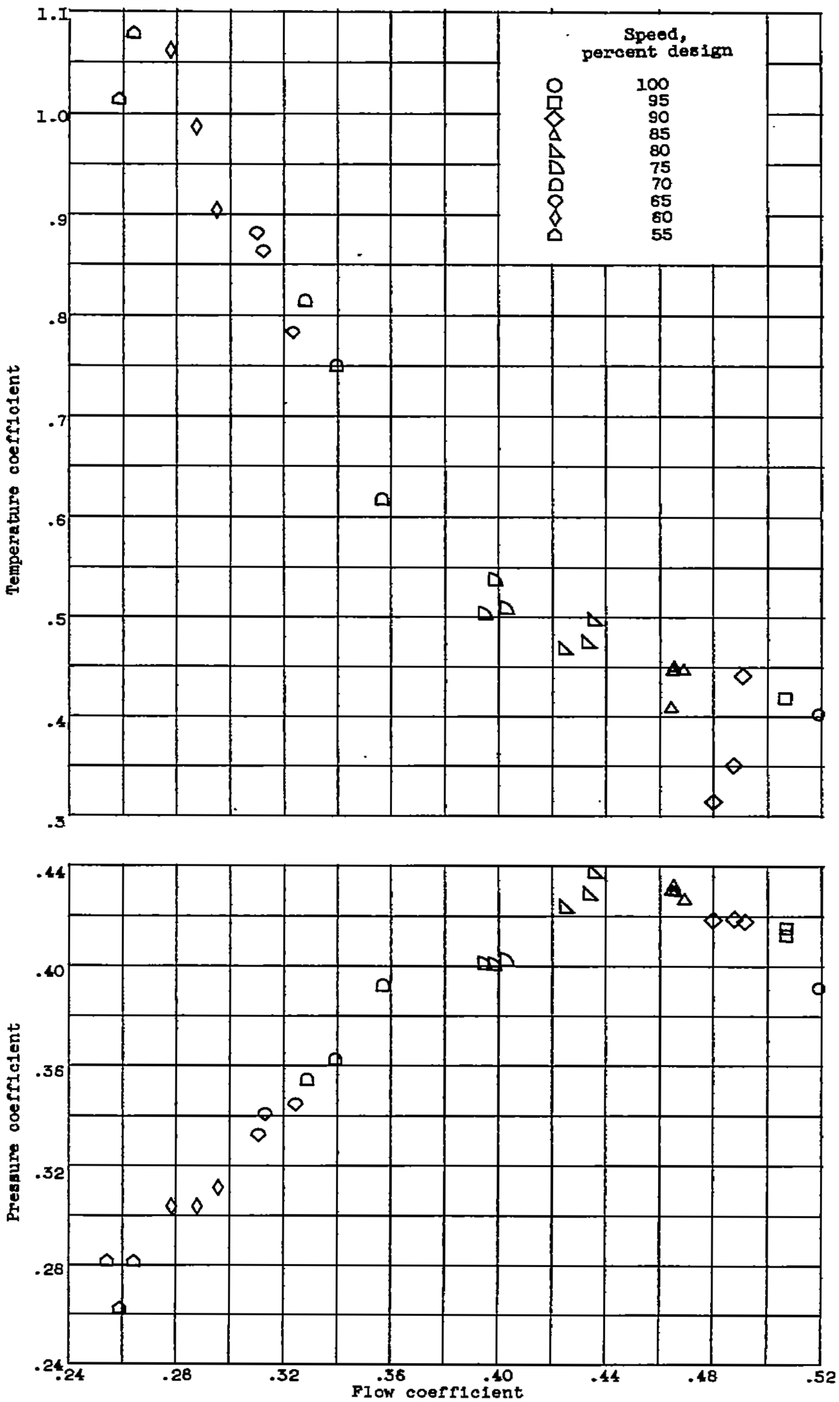
Figure 2. - Effect of guide-vane angle on compressor performance.



(b) Total-pressure ratio and adiabatic temperature-rise efficiency.

Figure 2. - Concluded. Effect of guide-vane angle on compressor performance.

3901

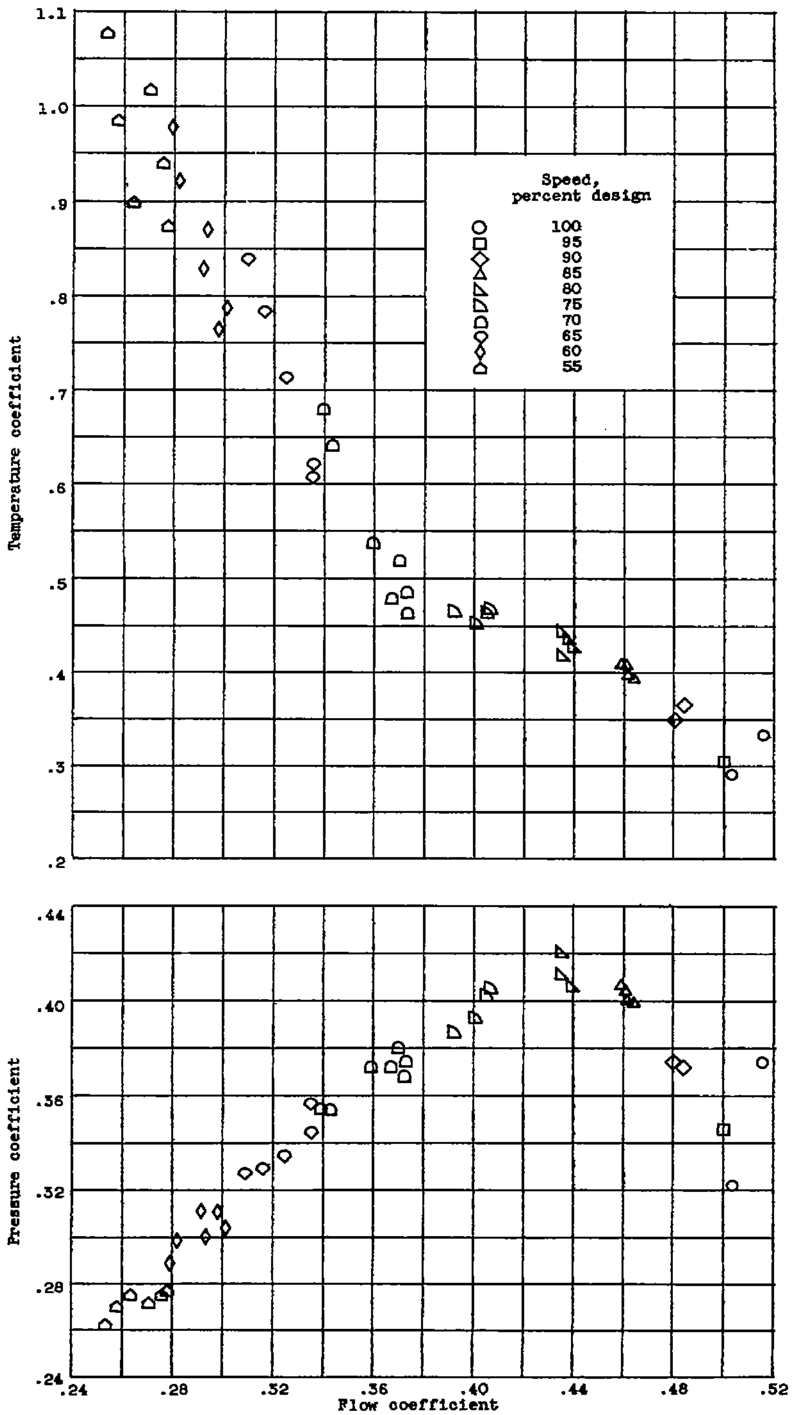


(a) Guide-vane angle, -7°.

Figure 3. - First-stage performance.

[redacted]

3901

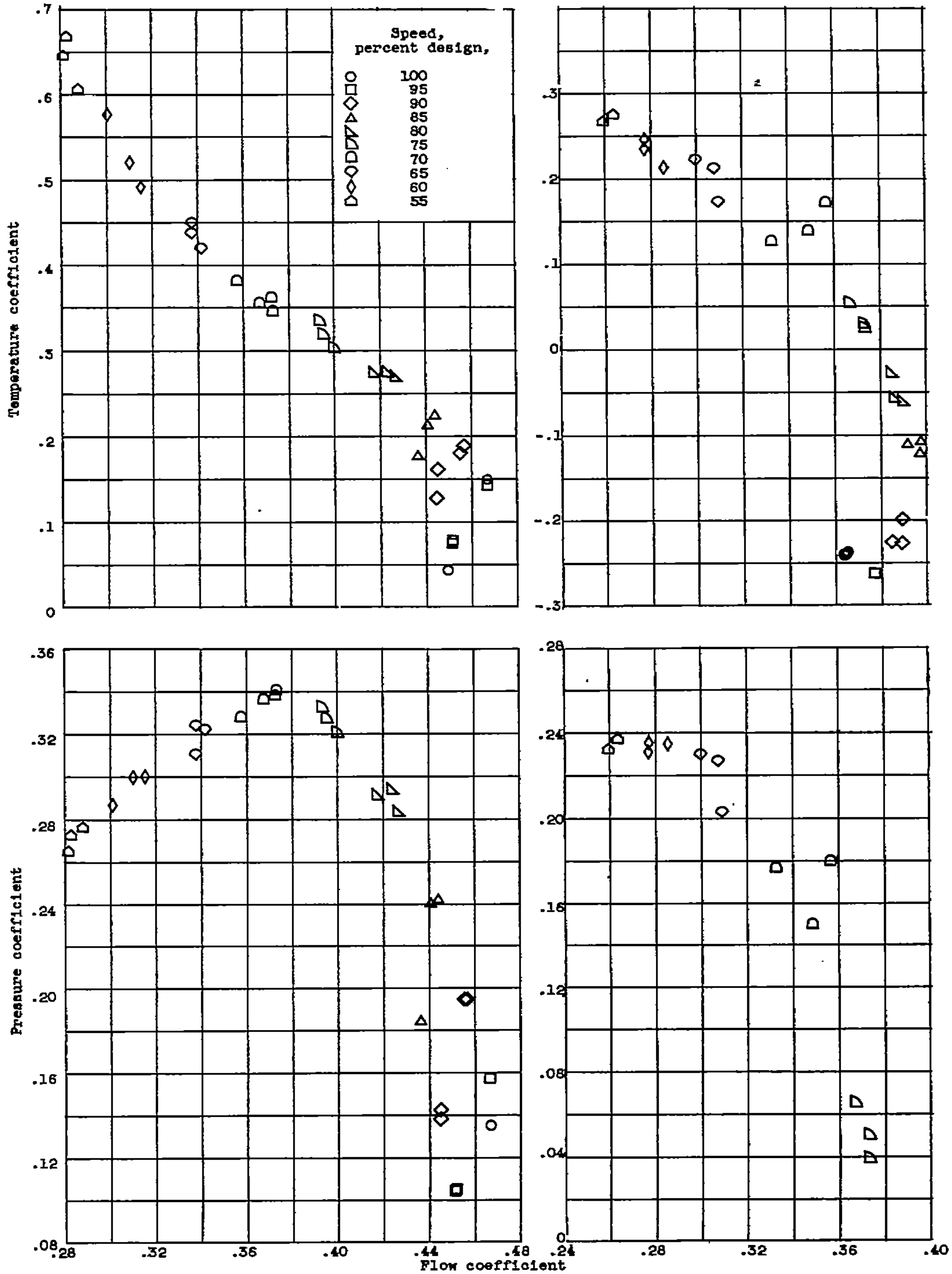


(b) Guide-vane angle, 0°.

Figure 3. - Continued. First-stage performance.

[redacted]

3901

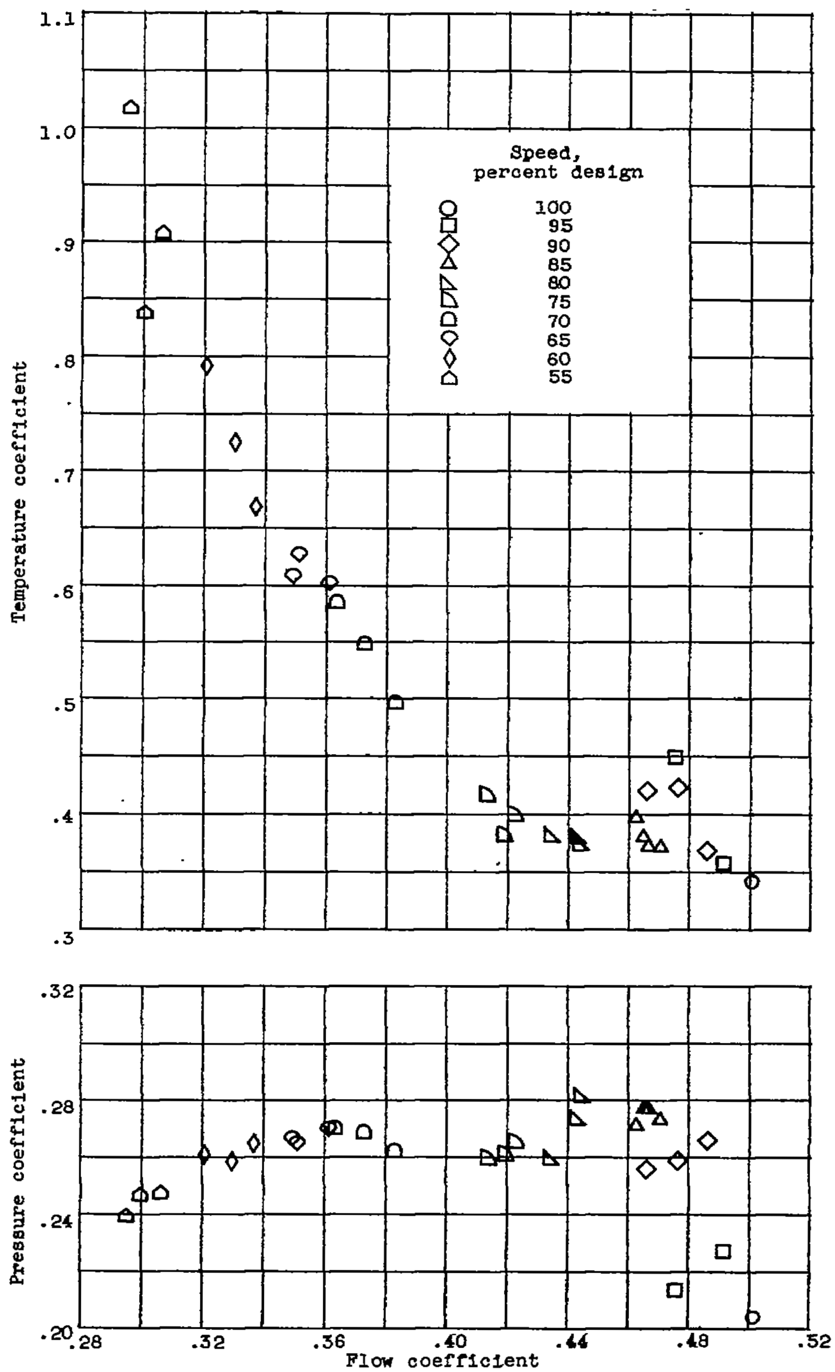


(c) Guide-vane angle, 14°.

(d) Guide-vane angle, 29°.

Figure 3. - Concluded. First-stage performance.

3901

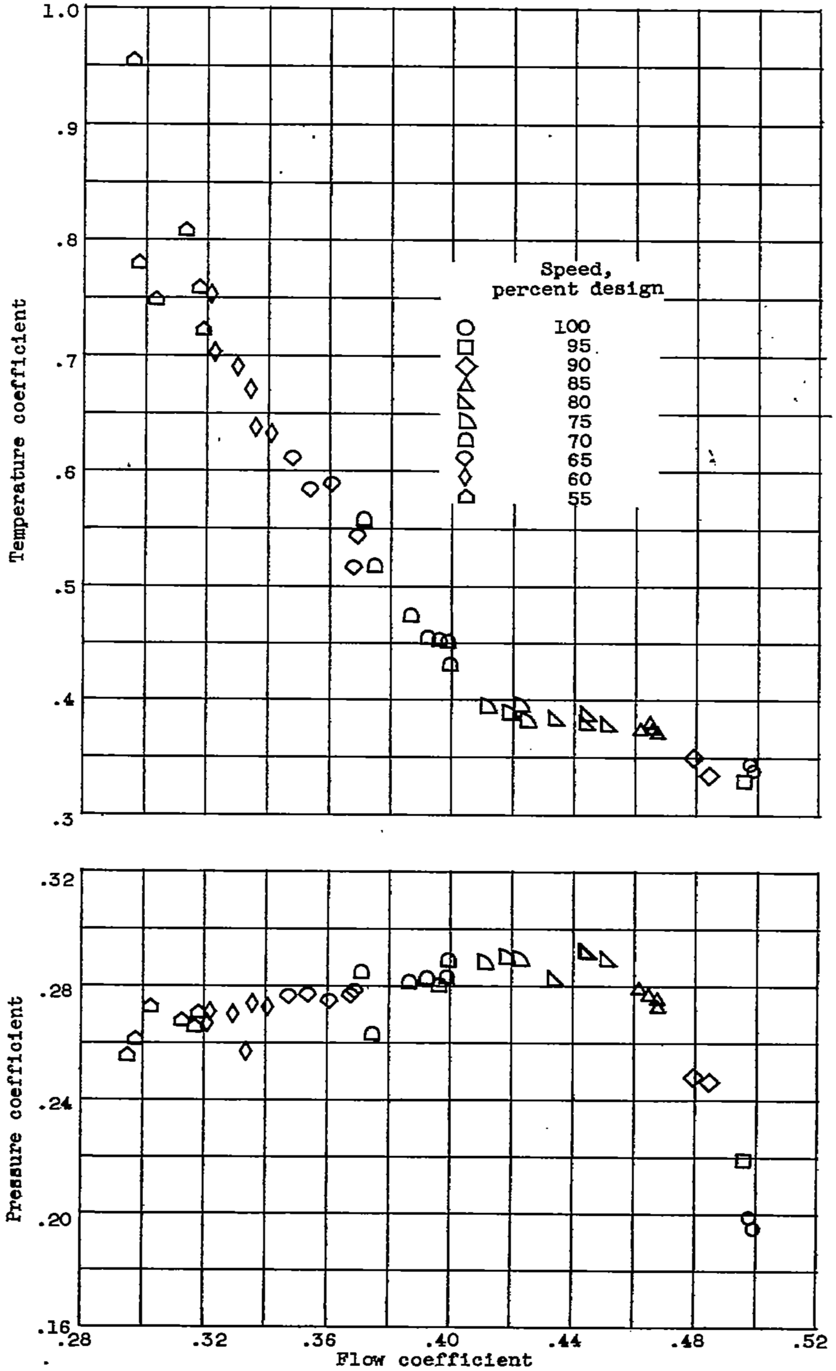


(a) Guide-vane angle, -7°.

Figure 4. - Second-stage performance.

3901

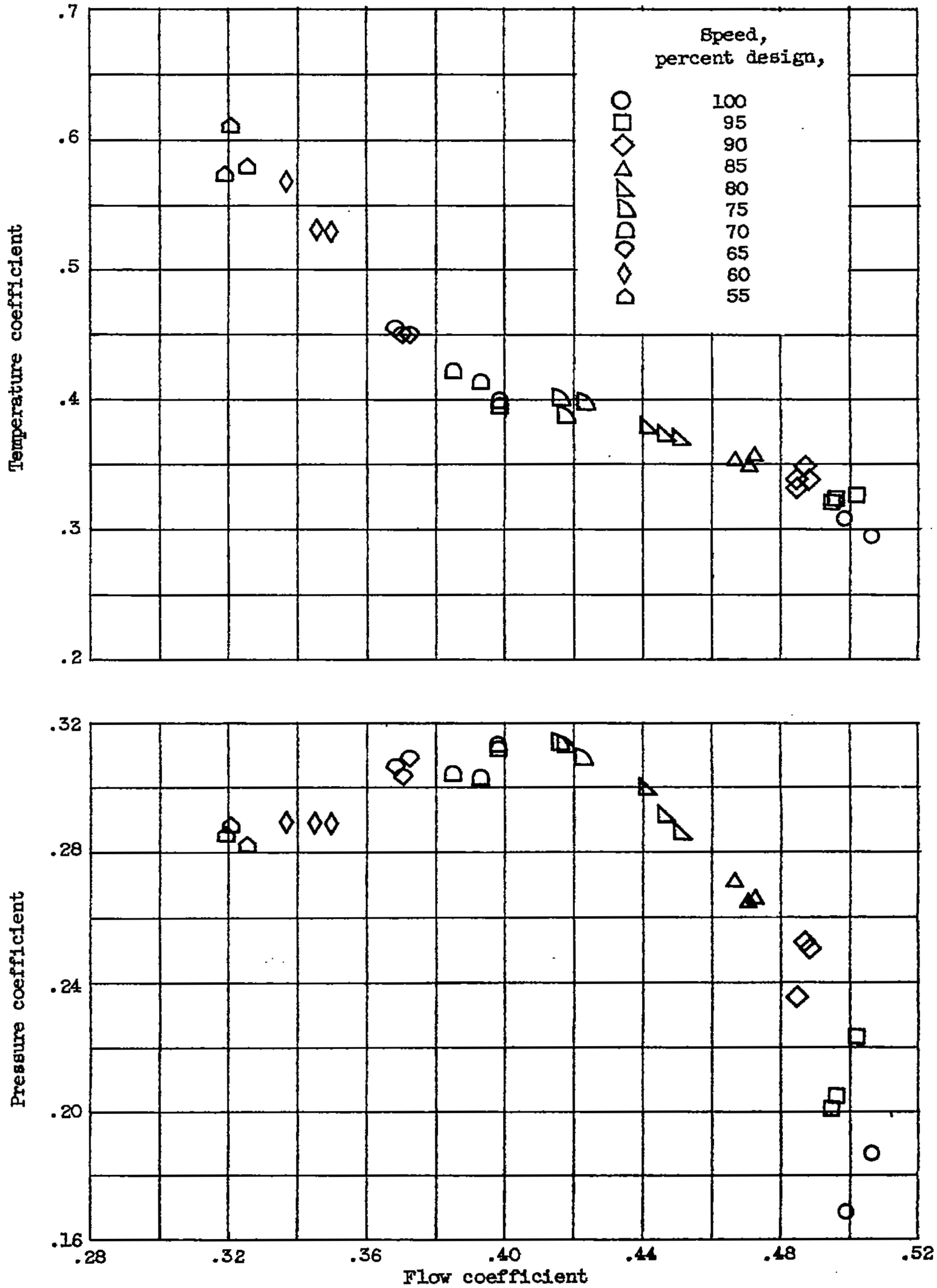
CV-3



(b) Guide-vane angle, 0°.

Figure 4. - Continued. Second-stage performance.

[redacted]

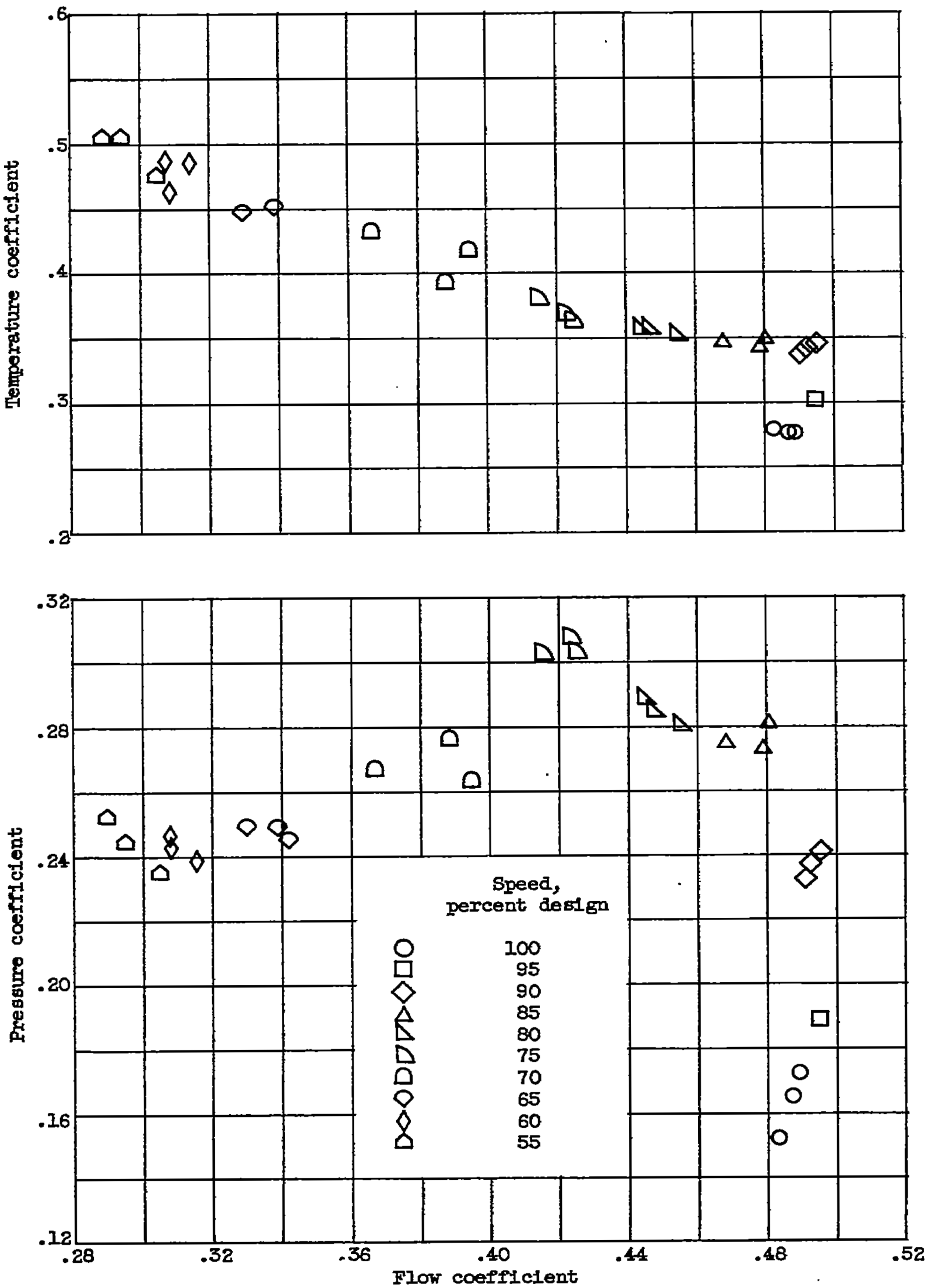


(c) Guide-vane angle, 14°.

Figure 4. - Continued. Second-stage performance.

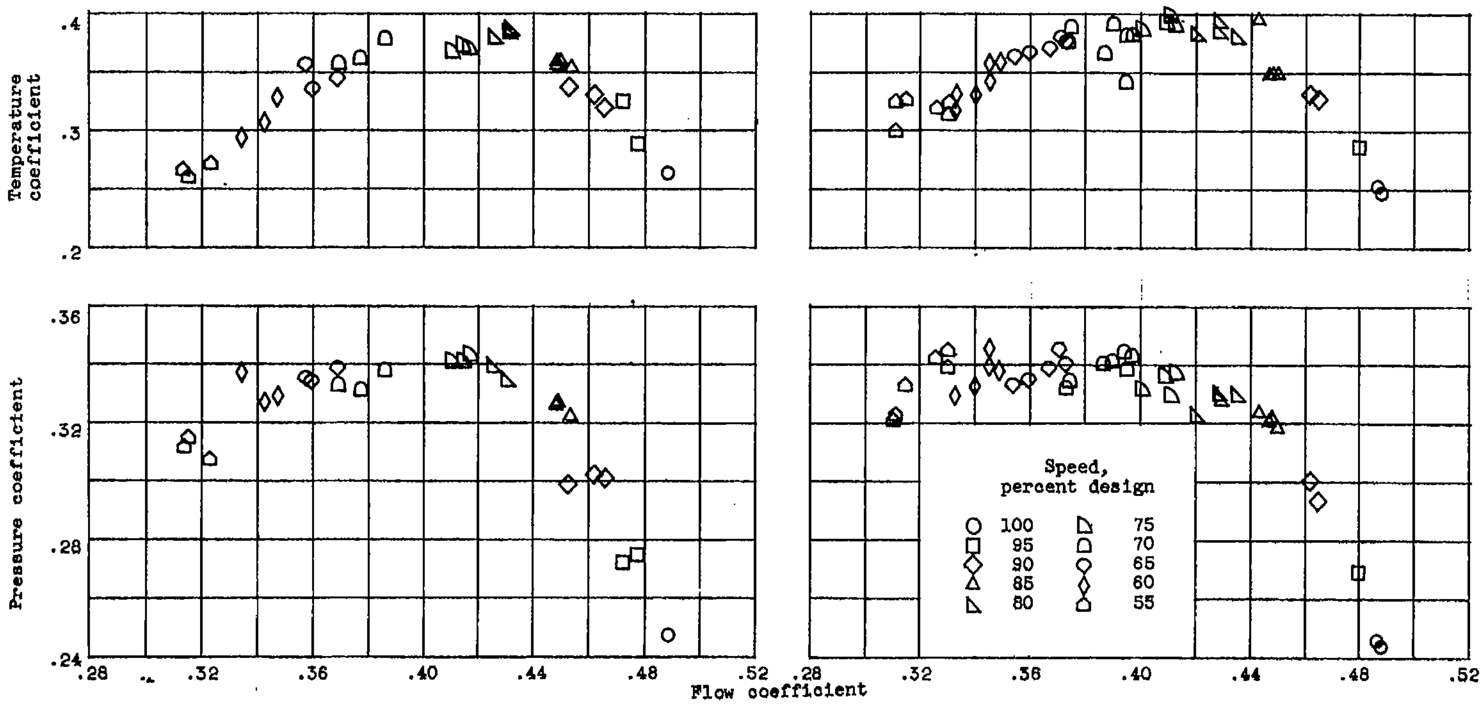
[redacted]

3901
CV-3 back



(d) Guide-vane angle, 29°.

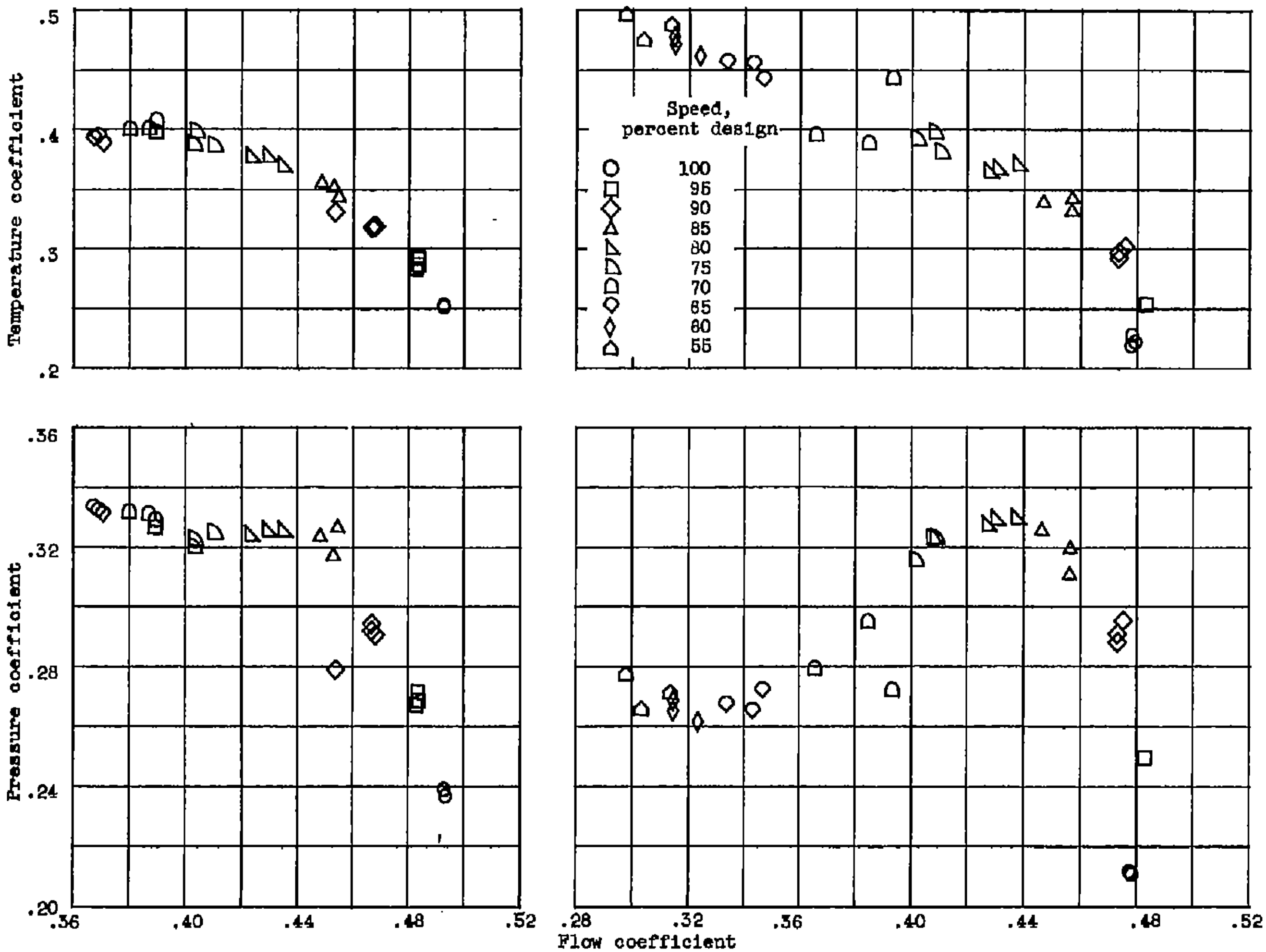
Figure 4. - Concluded. Second-stage performance.



(a) Guide-vane angle, -7°.

(b) Guide-vane angle, 0°.

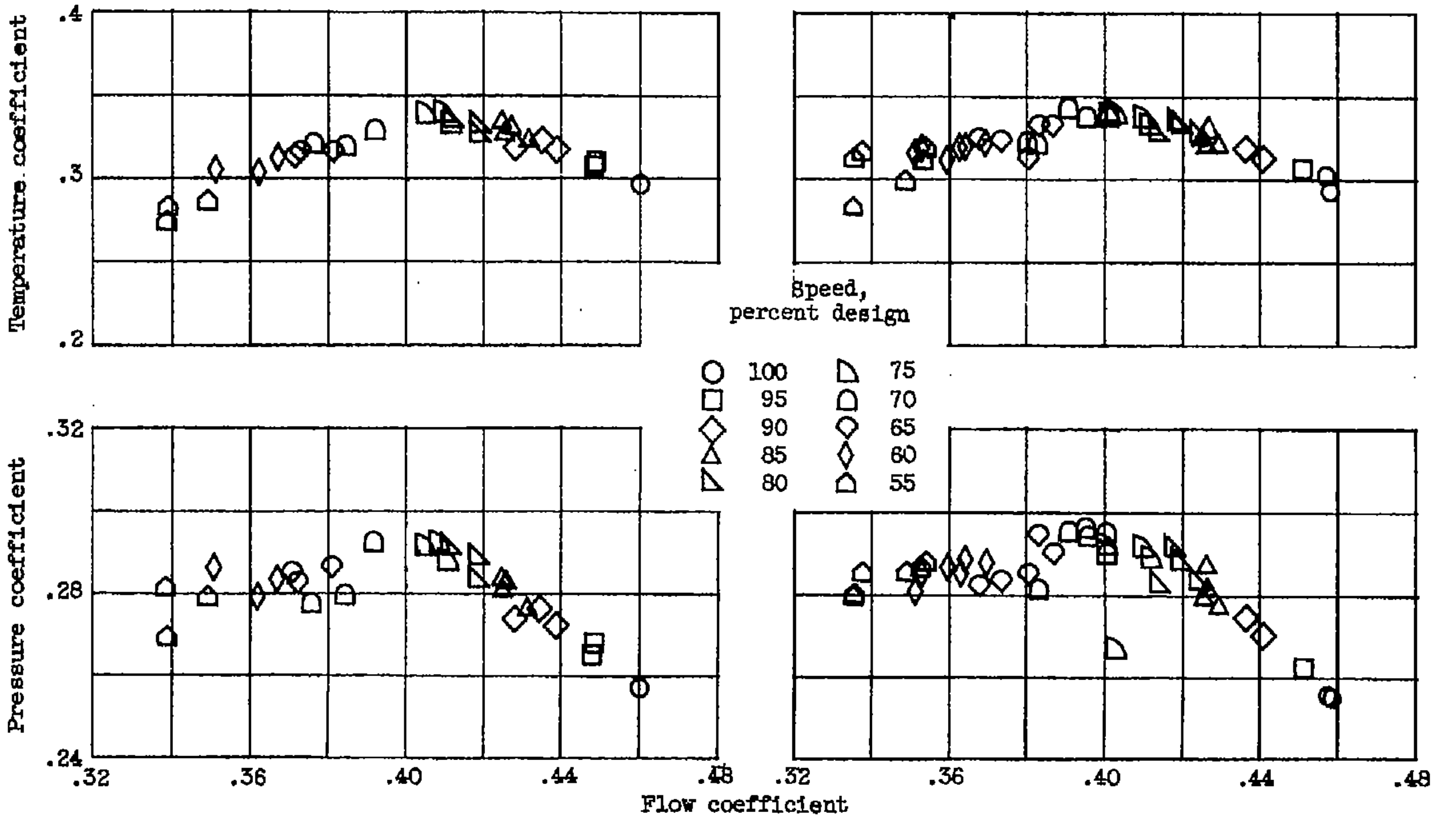
Figure 5. - Performance of third and fourth stages.



(c) Guide-vane angle, 14°.

(d) Guide-vane angle, 29°.

Figure 5. - Concluded. Performance of third and fourth stages.

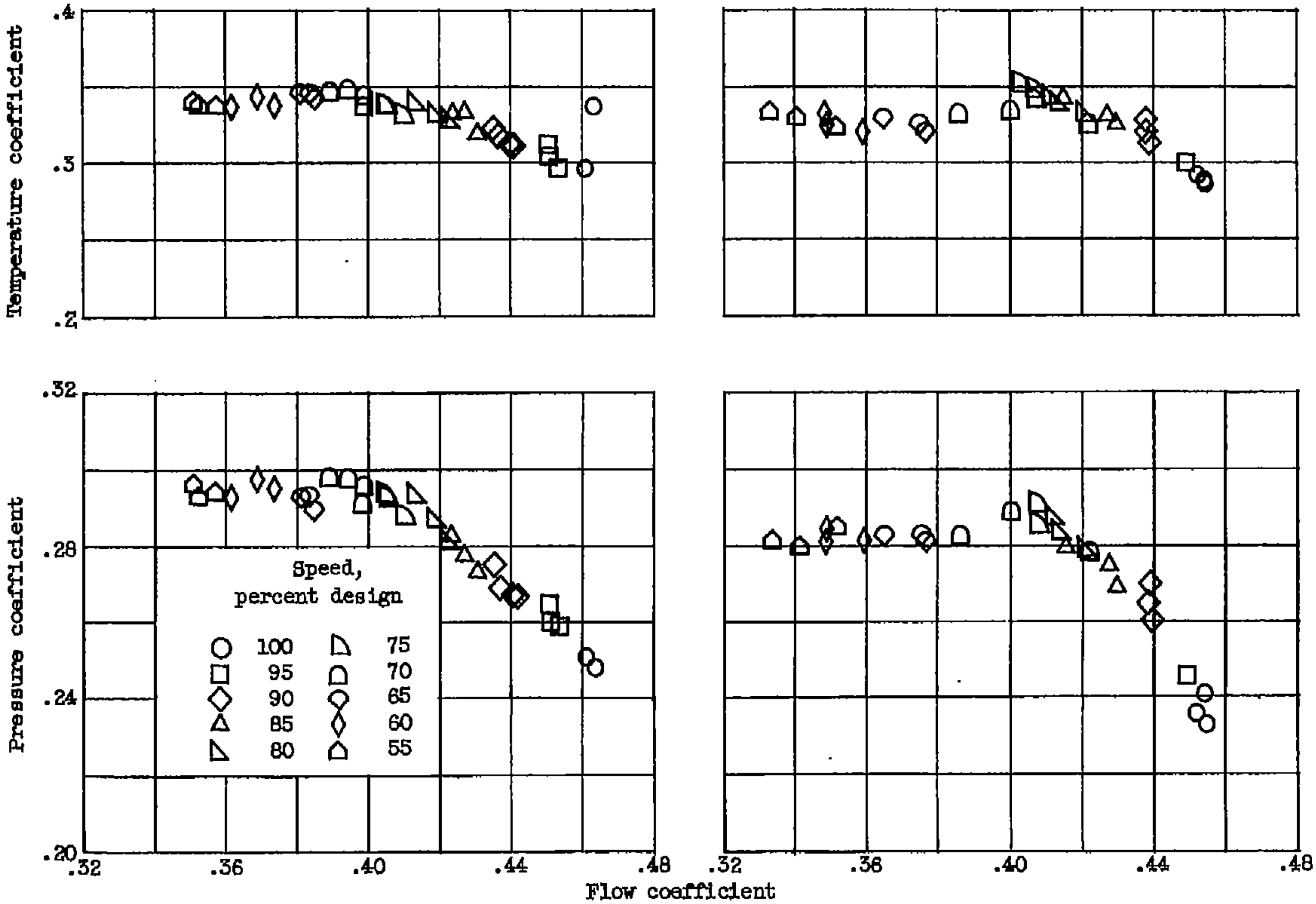


(a) Guide-vane angle, -7°.

(b) Guide-vane angle, 0°.

Figure 6. - Performance of fifth to ninth stages.

[redacted]

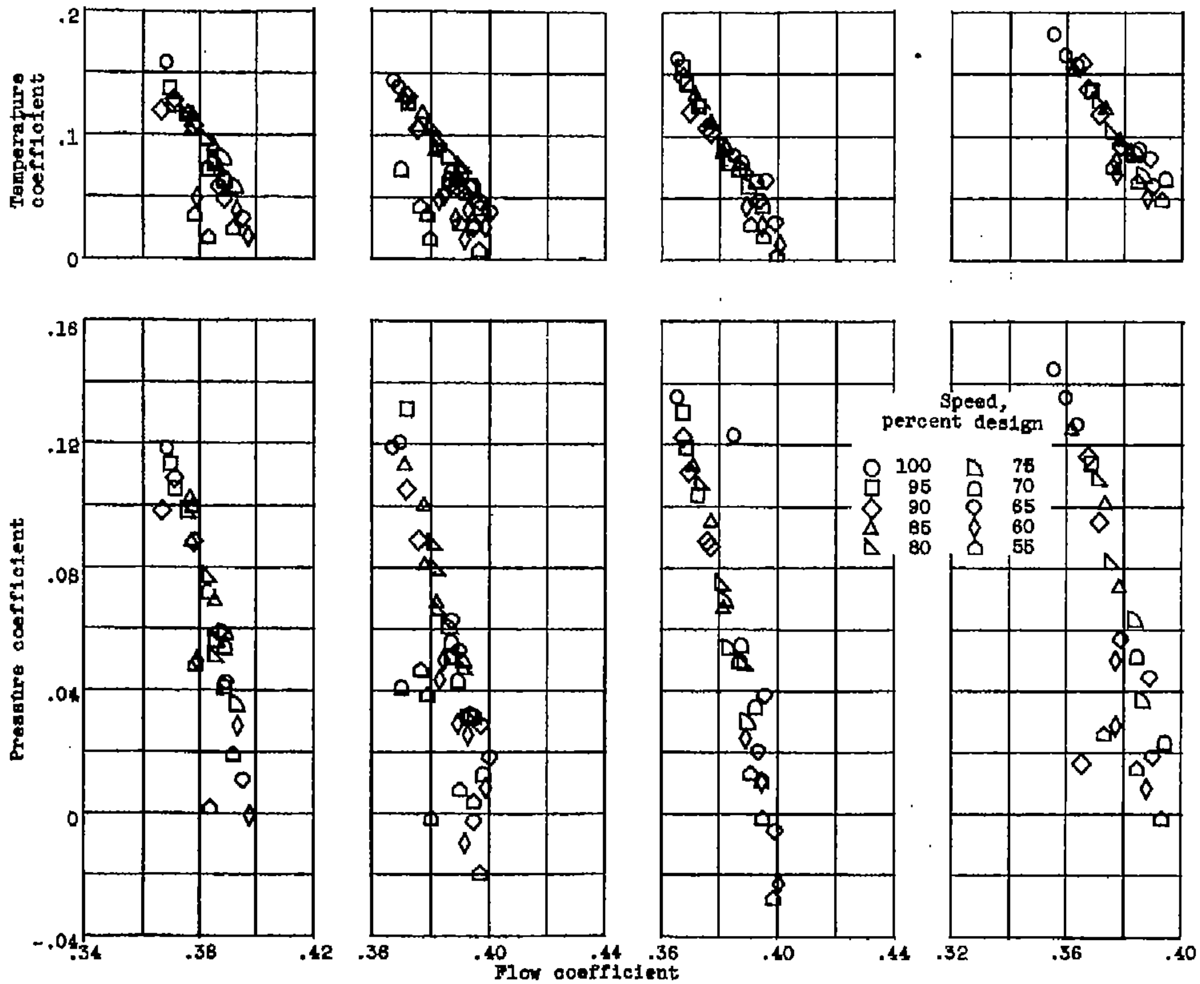


(c) Guide-vane angle, 14°.

(d) Guide-vane angle, 29°.

Figure 6. - Concluded. Performance of fifth to ninth stages.

[redacted]



(a) Guide-vane angle, -7°.

(b) Guide-vane angle, 0°.

(c) Guide-vane angle, 14°.

(d) Guide-vane angle, 29°.

Figure 7. - Performance of tenth to thirteenth stages.

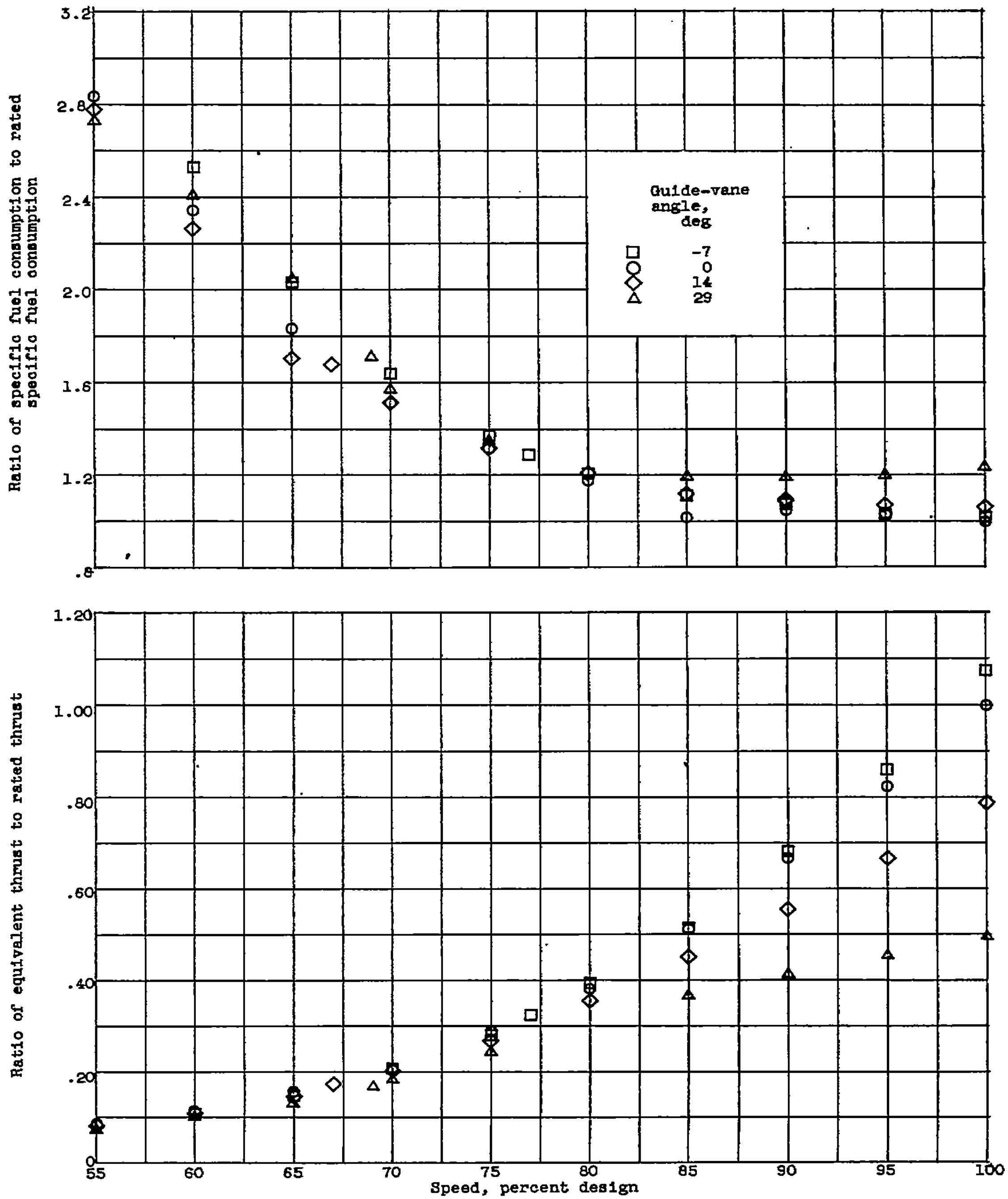


Figure 8. - Effect of guide-vane angle on equivalent thrust and specific fuel consumption.

[redacted]

NASA Technical Library
3 1176 01435 4493

[redacted]